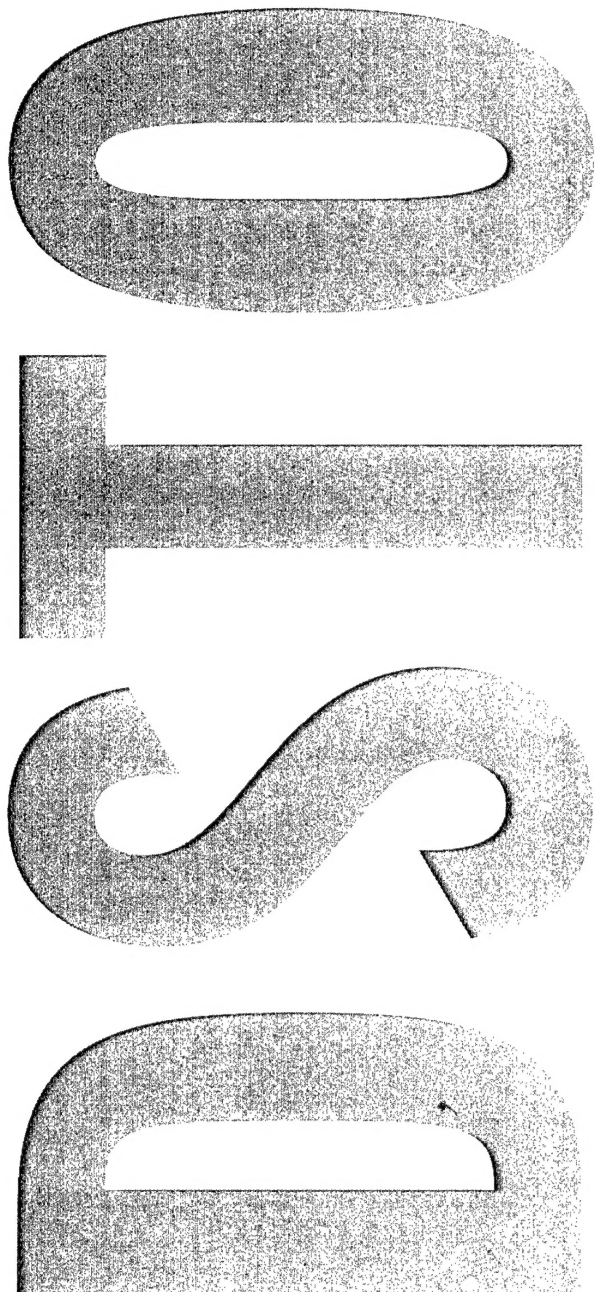**Australian Government**

Department of Defence

Defence Science and
Technology Organisation

A Comparison of the Predictive Accuracy of Human Thermoregulatory Models

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Chemical, Biological, Radiological and Nuclear Defence Centre
Platforms Sciences Laboratory

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ABSTRACT

The core temperature predictions from four computer models of the human thermoregulatory response were compared with results from laboratory exercise studies published locally and in the open literature. Although none of the models were able to predict deep body temperatures to within an accuracy of 0.1°C to 0.5°C in all instances, the model from the United States Army Research Institute of Environmental Medicine (ARIEM) in the form modified by DSTO performed better than the original and better than the rational models published by Xu and Werner and by Lotens and Havenith. However these latter two models are amenable to incremental improvements resulting from relatively small studies and it is therefore recommended that their development be continued at DSTO.

RELEASE LIMITATION

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APPROVED FOR PUBLIC RELEASE

A Comparison of the Predictive Accuracy of Human Thermoregulatory Models

Executive Summary

Exercise undertaken in thermally stressful environments can profoundly affect personal comfort, health and performance. With deployment of large elements of the Australian Defence Force to the north of Australia, the development of suitable strategies for thermal stress management is paramount for maintaining adequate performance in tropical environments.

Computer models for prediction of thermal strain have been developed to provide field commanders with information on human factors aspects of military operations. Such information has the potential to improve military planning processes, resulting in a reduction of heat casualties and lowering of the burden on medical logistics. A model developed by the US Army Research Institute of Environmental Medicine (ARIEM) has been widely used by the US Army during the Gulf war and other peace-keeping missions in Africa and S. E. Asia.

The core temperature predictions from four computer models of human thermoregulatory response – by an ARIEM model, by a Defence Science and Technology Organisation, Australia (DSTO) modified ARIEM model, by the model from Xu and Werner (Xu/Werner model) and by the model from Lotens and Havenith (Lotens/Havenith model) – were compared with oesophogeal and/or rectal temperature responses recorded during laboratory studies at DSTO and overseas laboratories. For the purposes of this comparison, an accurate prediction was defined to be one which agreed with experimental observation within (ideally) 0.1°C and up to the 0.5°C difference which may be observed between subjects with similar physical and fitness characteristics undergoing the same exercise protocol in the laboratory. The experimental subjects exercised for between 30 and 140 minutes mostly without intervening rest periods at between 325 watt and 985 watt total metabolic rate in temperatures which ranged from 20°C to 49°C and humidity which ranged between 20% RH and 79% RH. Most were clothed in shorts, T-shirts and runners, although the local study was conducted in Australia's Disruptive Pattern Combat Uniform (DPCU).

Although none of the models produced predictions which agreed with experimental observations in all instances, the ARIEM model as modified by DSTO [12] performed better more often than the other models. The original ARIEM model tended to predict temperatures which were too high, especially at moderate to high work rates although the shape of the temperature-time curve approximated the experimental results. The Xu/Werner model often predicted temperatures which were lower than the experimental results. The Lotens/Havenith model consistently predicted an initial overly rapid rise in temperature which then stabilised to a relatively constant temperature which often

approximated the final experimental temperature if the exercise protocol was sufficiently extended.

Further development of the ARIEM model will require extensive laboratory studies that are considered unlikely to be supported in Australia. The Xu/Werner and Lotens/Havenith models however are suited to improvement on an incremental basis that will not require large laboratory studies and it is therefore recommended that the development of these two models be pursued.

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Contents

1. Introduction

Computer programs have been developed over many years for simulation of physiological responses to exercise under differing conditions. Wissler [1] published a 'rational' model in 1962 which was based on the thermodynamic theory of heat exchange between the environment and a collection of 250 nodes simulating the human body parts and modified by some experimentally determined processes of human thermoregulatory response. This was followed in 1971 by the 25-node model of Stolwiljk [2] and in 1972 by the 2-node model of Gagge [3]. Also in 1972, Givioni and Goldman [4] at the United States Army Research Institute for Environmental Medicine (ARIEM) published an 'empirical' model which differed from the earlier developments in that it depended predominantly on simple regression analysis of experimental data obtained from subjects working at different rates in laboratory simulated environments wearing a variety of clothing ensembles. Evolution of this model has continued with elaborations by Gonzales et al [5] in 1997 and Cadarette et al [6] in 1999.

In 1993 Werner and Webb [7] published a refinement of the Gagge model which extended it to 12 nodes and added further thermodynamic processes and thermoregulatory functions. Also published in 1993 was the formulation by Lotens [8] of a substantial multi-layer clothing model overlaying the Gagge physiology model. As development continued Xu and Werner [9] published a model (Xu/Werner model) which draws on the physiological models of Stolwiljk [2] and of Werner and Webb [7], overlaid by a simple clothing model which is capable of simulating a single layer of cloth and the associated trapped air layer. The Xu/Werner model uses six cylinders, one each for the head, torso, arms, hands, legs and feet. The total surface area of these cylinders is set to be the same as the modelled subject. Each cylinder consists of four coaxial layers: the skin, the fat layer, the muscle and finally the core which represents the viscera and bone. Heat is produced in all layers with the muscle layer simulating the metabolic heat generated as a result of external work. The fat layer simulates the subdermal fat in the subject, the skin layer approximates the region where the thermoregulatory responses of sweating and vasodilation occur and the core is considered to participate only in the storage of heat. Surrounding each of the cylinders there may be an additional clothing layer separated from the skin by an air gap.

In 2001, Havenith [10] published physiological elaborations for the model of Lotens [8] which allow the level of aerobic fitness and of heat acclimatisation of the modelled subject to be taken into account. This Lotens/Havenith model approximates the human body by a single cylinder in which the physiology-based part of the model is implemented. The cylinder has the same length and surface area as the subject and is composed of two layers. The outer layer is several millimetres thick and represents the skin of the human subject in which thermoregulatory processes such as sweating and vasodilation occur. The remainder of the cylinder volume represents the muscle, fat, viscera and bone in which metabolic heat is generated, stored and distributed by the circulatory system to the skin. Outside this cylinder are three further layers: an under-

clothing layer and an outer clothing layer separated by an air gap. The under-clothing is assumed to be form-fitting so that there is no air gap between it and the skin. Further, the exposed areas of clothing and skin are treated differently whether or not they are subjected to infra-red and/or UV/visible electromagnetic radiation.

Through bi-lateral collaboration between Australia and The Netherlands, the Chemical, Biological, Radiological and Nuclear Defence Centre (CBRNDC) at Defence Science and Technology Organisation (DSTO) has received all source code for the Lotens/Havenith model. Also, Dr Xu has provided the source code for his Xu/Werner model and DSTO has published [11] a Givioni and Goldman [4] (ARIEM) model for Microsoft Windows 95/98/NT/ME/2000 and has modified that model [12] by regression fitting against locally obtained experimental data to produce the ARIEM_MOD model. The availability of all these models has provided an opportunity to compare their performance in thermal strain prediction.

2. Method

2.1 Data Requirements

To optimise the validity of comparisons of the various models against measured data, it was required that studies be conducted under controlled laboratory conditions with full sets of parameters for inputs into the models, or that sufficient details are available to allow independent determination of some of the variables. For example, the papers found during a literature search did not specify all of the physical properties of the clothing and footwear worn by the subjects. Examination of locally available examples allowed some parameters to be measured (eg. thickness, density) and others to be located in reference texts (eg. insulation, vapour resistance, regain). The selection of studies in which subjects wore minimal clothing served to minimise any bias introduced by this treatment. As none of the models are able to calculate the effects of dehydration, a further requirement was that the hydration status of the subjects in the studies be controlled at the euhydrated level throughout and this control be specified by the researchers in their published findings. In addition, body fat content is a required input for the Lotens/Havenith and Xu/Werner models but this parameter was not reported by most of the studies. In two studies at ARIEM however, the body fat content of the subjects was reported as 20%, so this value was assumed for all the studies where body fat content was not reported. In some of the studies, the researchers did not specify a wind velocity although it is a common practice in such work to employ some kind of forced ventilation assistance – it is also a common practice to use no ventilation assistance in air-conditioned surroundings. Since no other data were available, the absence of forced ventilation was assumed where none was specified.

2.2 Experimental Data

A literature search uncovered five research papers which published the results of laboratory-based studies of appropriate type and in sufficient detail to allow for a comparison between measured data and predicted values. In 1980 Nadel et al [13] published data for which subjects dressed in shorts and shoes rested for 30-40 minutes and then exercised for 30 minutes on a cycle ergometer. In 1983 Sawka et al [14] published data for which subjects dressed in gym shorts, tee-shirts and tennis shoes performed four cycles of ten minutes rest and twenty-five minutes exercise in one continuous 140 minute session on a treadmill. Melin et al [15] have published data for which subjects dressed in shorts and shoes exercised on a treadmill for 100 minutes and in 1998 Montain et al [16] published data for which subjects dressed in shorts, socks and athletic shoes exercised for 50 minutes on a treadmill. In addition, data was available from a trial conducted by Amos and Egglestone [17] in which young male subjects exercised for 100 minutes on a treadmill wearing the standard Australian Army Disruptive Pattern Combat Uniform (DPCU).

2.3 Comparison Procedure

Subjects' particulars (height, weight, percent of body fat, aerobic fitness level as estimated by VO_2peak values), environmental factors (ambient temperature, relative humidity, ambient wind speed), clothing characteristics (thermal resistance, vapour resistance, regain, thickness, density, air gap) and work-related parameters (total metabolic rate, effective wind speed) were entered into each of four computer models: ARIEM, Xu/Werner, Lotens/Havenith and ARIEM_MOD. Where necessary some assumptions and estimates were made (eg. the percent body fat and ambient wind speed). All relevant data were collated in spreadsheets along with the reported experimental results on a study-by-study basis then plotted on common axes for comparison. The errors in core temperatures achieved at the end of exercise were tabulated and where intermediate values were available from the papers, root mean square differences between calculated and experimental core temperatures were also tabulated.

In determining what an acceptable error in prediction accuracy would be it is necessary to consider the source of the data. In general, body core temperatures are recorded with a precision of 0.1°C. Clearly, agreement of predicted values with measured values to this level of precision will always be acceptable accuracy, however lesser levels of precision may also be useful. It is commonly observed that subjects with similar physical characteristics and physical fitness undergoing identical experimental protocols may differ in their observed core temperatures by as much as 0.5°C or more [17] so model results would also be just acceptable if agreement within 0.5°C was achieved.

3. Results

3.1 Tables: Errors in the Prediction of Core Temperatures

Table 1 shows the end-point prediction errors for each of the models when compared with the data in the named study.

Table 1a. Comparison of model core temperature errors at data endpoints.

Model	Nadel et al [13]	Sawka et al [14]			Melin et al [15]
		20°C, 40% RH	35°C, 79% RH	49°C, 20% RH	
ARIEM	0.41°C	-0.04°C	0.04°C	-0.24°C	0.93°C
ARIEM_MOD	0.07°C	-0.49°C	-0.34°C	-0.36°C	-0.10°C
Xu/Werner	-0.55°C	-0.58°C	-0.49°C	-0.06°C	-1.55°C
Lotens/Havenith	0.25°C	Not Avail.	Not Avail.	Not Avail.	-0.70°C

Table 1b. Comparison of model core temperature errors at data endpoints (continued).

Model	Montain et al [16]			Amos and Egglestone [17]	
	25% VO$_2$peak	45% VO$_2$peak	65% VO$_2$peak	30°C, 60% RH	40°C, 30% RH
ARIEM	0.16°C	0.22°C	-1.14°C	0.83 °C	1.06°C
ARIEM_MOD	-0.08°C	-0.14°C	-0.7°C	0.09 °C (a)	0.34°C (a)
Xu/Werner	-0.28°C	-0.27°C	-0.66°C	-0.64°C	-0.58°C
Lotens/ Havenith	0.10°C	0.45°C	0.40°C	0.14°C	0.40°C

Note (a): These data are not valid for evaluation of the ARIEM_MOD model – see text.

Table 2 shows the Root Mean Square (RMS) difference between model output and intermediate core temperature measurements obtained from the named studies. Not all of the suitable studies reported intermediate values, some only reported an end-point temperature.

Table 2. Comparison of Root Mean Square errors in available data

Model	Nadel et al [13]	Melin et al [15]	Amos and Egglestone [17]	
			30°C, 60% RH	40°C, 30% RH
ARIEM	0.26°C	0.68°C	0.55°C	0.64°C
ARIEM_MOD	0.25°C	0.07°C	0.06°C **(b)**	0.19°C **(b)**
Xu/Werner	0.50°C	0.97°C	0.46°C	0.36°C
Lotens/Havenith	0.35°C	0.39°C	0.39°C	0.55°C

Note (b): These data are not valid for evaluation of the ARIEM_MOD model – see text.

3.2 Comparison 1: (Data from Nadel et al [13])

These authors stated that four relatively fit male subjects rested for 35-40 minutes on a cycle ergometer seat indoors in an ambient temperature of 35°C and 36% Relative Humidity (RH) dressed only in shorts and shoes. Wind velocity was not specified and assumed to be normal air-conditioning levels of 0.1 – 0.2 $m.s^{-1}$. They then exercised at a total metabolic rate of 750 watt (55% of VO_2peak level) for 30 minutes. The average age of the subjects was 31 years, height 179 cm, weight 79.9 kg, VO_2peak 56.8 $ml.min^{-1}.kg^{-1}$. Exercise occurred primarily in the spring in Connecticut, USA, so unacclimatised subjects are assumed for the Lotens/Havenith, ARIEM and ARIEM_MOD models. Body fat levels were not specified so 20% was assumed for the Xu/Werner and Lotens/Havenith models. Results are plotted in Figure 1. The experimental data show a slightly greater rate of rise in body core temperature (Tc) in the first 7 minutes of exercise than is evident later in the session. The ARIEM and ARIEM_MOD models both show a small drop in Tc to 5 minutes then adopt a relatively constant rate of rise. The ARIEM_MOD model generates a prediction which runs nearly parallel to the experimental data whereas the ARIEM model shows a steeper rate of rise. The Xu/Werner model shows a constant rate of rise throughout, however the Lotens/Havenith model begins with the initial higher rate of rise which parallels the initial rate of the experimental data and extends that rate to 20 minutes after which it adopts a rate of rise which again parallels the experimental data.
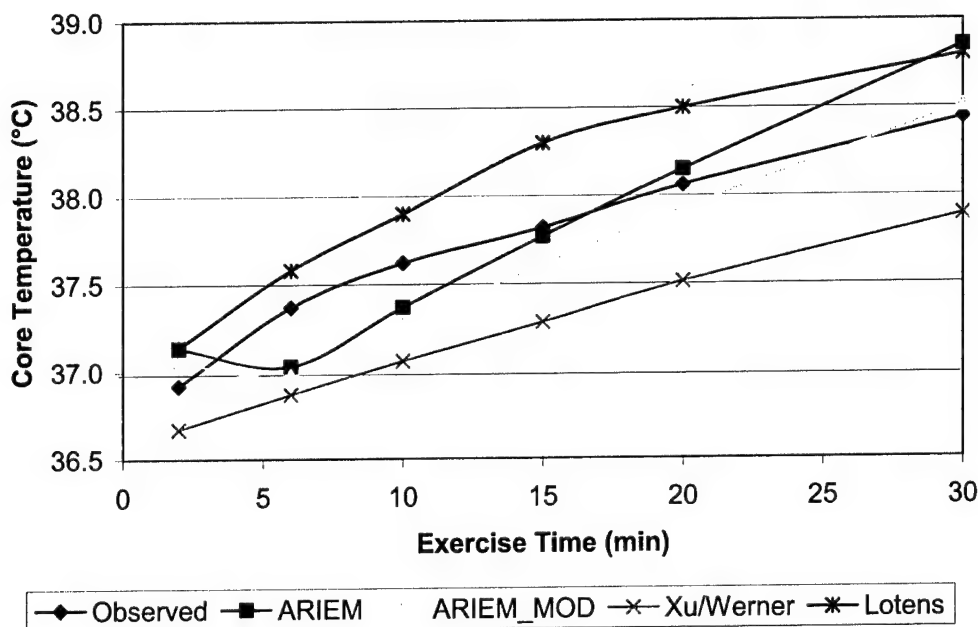
Figure 1. *Comparison of predicted core temperatures for four models with measured Tc from Nadel et al [13]*

3.3 Comparison 2: (Data from Sawka et al [14])

Six male subjects walked indoors at $1.34 \, m.s^{-1}$ on a level treadmill (325 watt total metabolic rate) in four cycles of 10 minutes rest and 25 minutes exercise accomplished in a single 140 minute session. Only the single data point at 140 minutes was published but the model output for the entire duration of the experimental protocol has been reported here to allow comparison between the models. Subjects wore tee-shirts, gym shorts and tennis shoes. Average age was 24 years, weight 75.5 kg, height 167.9 cm, body fat 20% by weight, VO_2peak $47.9 \, ml.min^{-1}.kg^{-1}$. The subjects had undergone 10 days of acclimatisation work immediately prior to the test. They worked in three environments: comfortable (20°C, 40% RH), hot-wet (35°C, 79% RH) and hot-dry (49°C, 20% RH). Only the three endpoint core temperatures were reported. Wind speed is not specified so a normal air-conditioning level of $0.1 - 0.2 \, m.s^{-1}$ is assumed. Results are plotted in Figures 2, 3 and 4. Note that because the Lotens/Havenith model as implemented is only capable of calculating up to three work/rest stages, model output is only available for the first 45 minutes of each session. In Figures 2, 3 and 4, the ARIEM model demonstrates good performance at the relatively low work rate reported and Table 1a shows very good agreement between the ARIEM model and the experimentally determined final core temperatures recorded at the three climatic conditions tested. Of interest with this model is a rapid rise followed by a rapid fall of

Tc between 120 and 140 minutes. This deviates from the trend of prediction for this exercise protocol in its initial 120 minutes which highlights the requirement for further refinement of this model. At this stage the reason for this deviation is unknown. Although the Lotens/Havenith model is unable to predict more than three stages of the eight work/rest stages used in this experimental protocol, the early rapid rate of rise in Tc displayed in Figures 3 and 4 is of concern in that it indicates a possibly large error if the work duration were to be extended without the intervening rest breaks. As shown in Table 1a, the Tc prediction of the ARIEM_MOD model is just within the 0.5°C tolerance in the comfortable condition and are substantially within this tolerance in the hot-humid and hot-dry conditions. Although the Xu/Werner model does have an error of only 0.06°C for the hot-dry environment it is just within tolerance for the hot-humid condition and outside tolerance in the comfortable condition. Since only the final Tc was reported in the experimental data, no RMS errors are available.
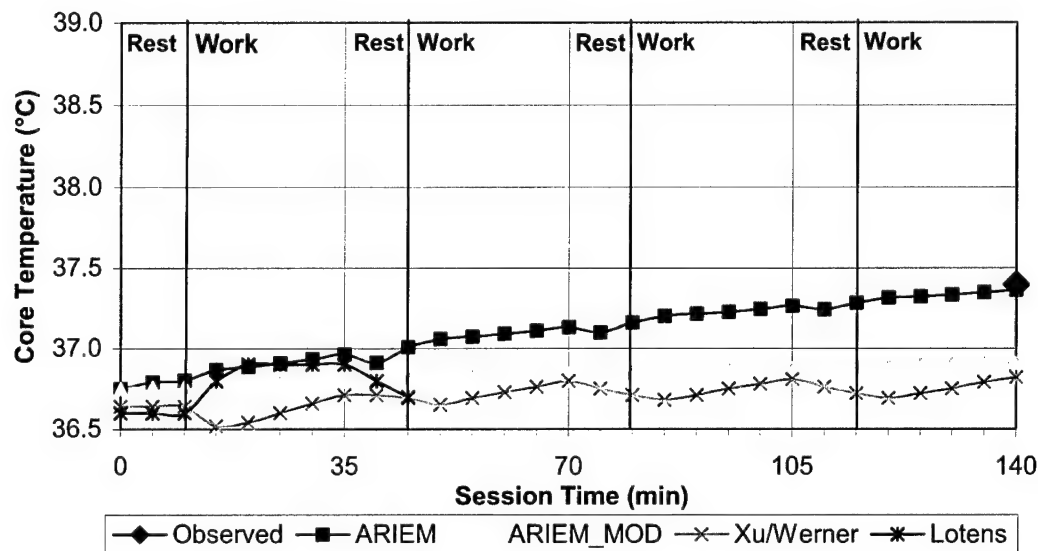

Figure 2. Comparison of predicted core temperatures from four models with the measured final Tc value reported by Sawka et al [14] data at 20°C and 40% RH. Lotens Model could only predict 3 stages or 1.5 cycles – see text.
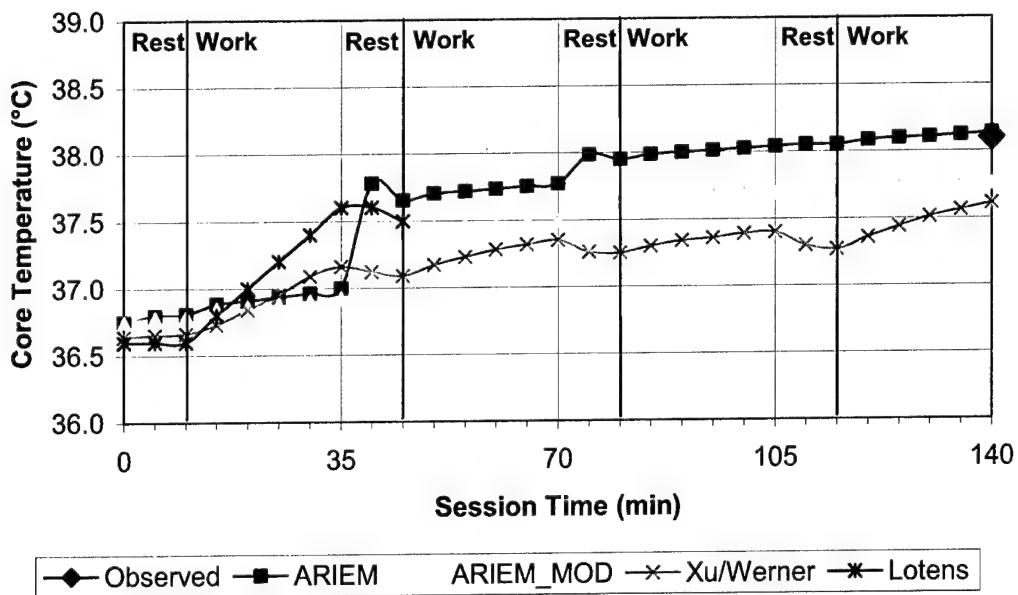
Figure 3. Comparison of predicted core temperatures from four models with the measured final Tc value reported by Sawka et al [14] at 35°C and 79% RH. Lotens Model could only predict 3 stages or 1.5 cycles – see text.
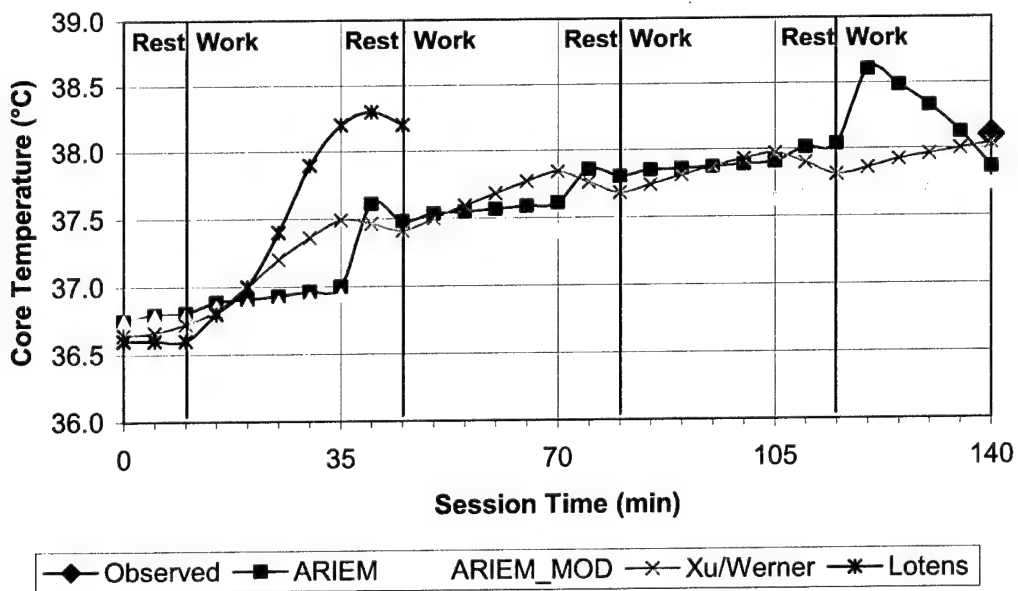

Figure 4. Comparison of predicted core temperatures from four models with the measured final Tc value reported by Sawka et al [14] at 49°C and 20% RH. Lotens Model could only predict 3 stages or 1.5 cycles – see text.

3.4 Comparison 3: (Data from Melin et al [15])

Five moderately trained male subjects, unacclimatised to heat and dressed in shorts and shoes exercised indoors in 35°C and 20-30% RH on a motor-driven treadmill at 640 watt total metabolic rate (50% of VO_2peak) for 100 minutes. Wind speed was not specified so a normal air-conditioning level of $0.1 - 0.2$ m.s^{-1} is assumed. Average age was 26 years, weight 64.8 kg, height 174 cm, VO_2peak 59.2 ml.min^{-1}.kg^{-1}. Body fat content of 20% was assumed. Experimental data and the corresponding model predictions are displayed in Figure 5. In this graph, the predictions by the Lotens/Havenith model show an initial rate of rise much greater than that shown by the experimental data, then adopts a constant-temperature plateau which is also not displayed by the experimental data. The Xu/Werner model shows an initial rate of rise similar to the observed data then a plateau temperature which is lower than the still-rising observed temperatures. The ARIEM model shows a continuing high rate of rise whereas the ARIEM_MOD model produces a prediction which closely follows the experimental data. The RMS errors reported in Table 2 reflect these differences with the ARIEM_MOD model displaying an RMS error of only 0.07°C over the exercise period.
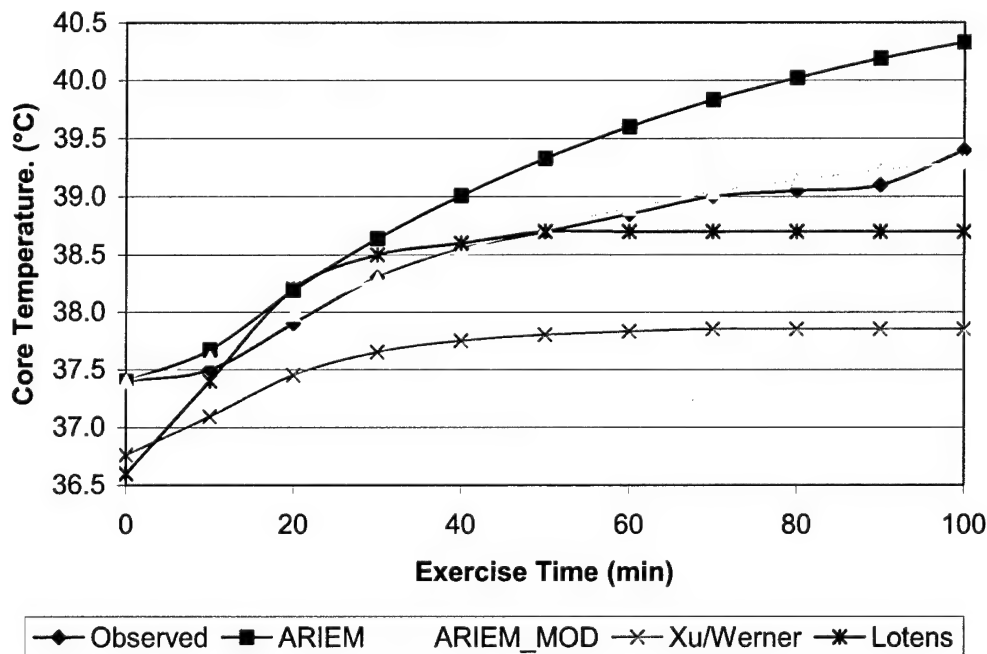

Figure 5. Comparison of predicted core temperatures from four models with measured Tc values reported by Melin et al [15]

3.5 Comparison 4: (Data from Montain et al [16])

Nine heat-acclimated men exercised indoors in 30°C, 50% RH, wind speed 1 m.s^{-1} for 50 minutes on a motor-driven treadmill. Exercise sessions were conducted at 25%, 45% and 65% of VO_2peak (379, 682 and 985 watt total metabolic rates respectively). Subjects' average age was 24 years, height 176 cm, weight 80.5 kg, VO_2peak 56.5 $\text{ml.min}^{-1}.\text{kg}^{-1}$. A body fat content of 20% was assumed. Results are plotted in Figures 6, 7 and 8. Only the final core temperature result is available from the experimental data. It is clear from Figure 8 that only the Lotens/Havenith model predicts a Tc response within 0.5°C of the observed values in the protocol for work at 65% VO_2peak. Table 1b shows errors in final Tc for this work protocol of between 0.4°C for the Lotens/Havenith model to –1.14°C for the ARIEM model. The ARIEM_MOD model performs acceptably at 45% VO_2peak while at 25% VO_2peak both the Lotens/Havenith and ARIEM_MOD models perform close to the 'ideal' 0.1°C prediction accuracy.
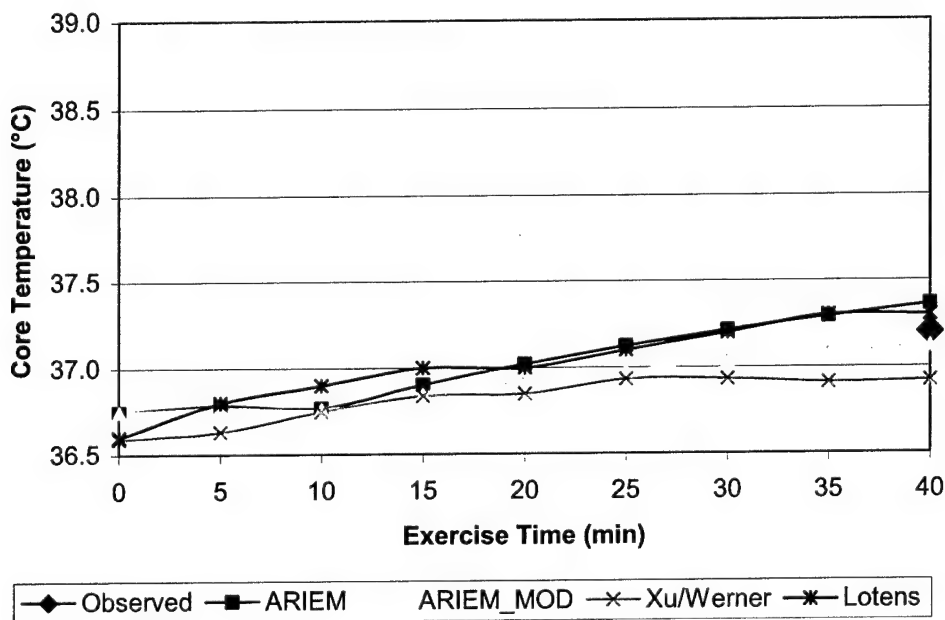

Figure 6. *Comparison of predicted core temperatures from four models with measured Tc values reported by Montain et al [16] data for exercise at 25% VO₂peak*

Figure 7. *Comparison of predicted core temperatures from four models with measured Tc values reported by Montain et al [16] for exercise at 45% VO2peak*

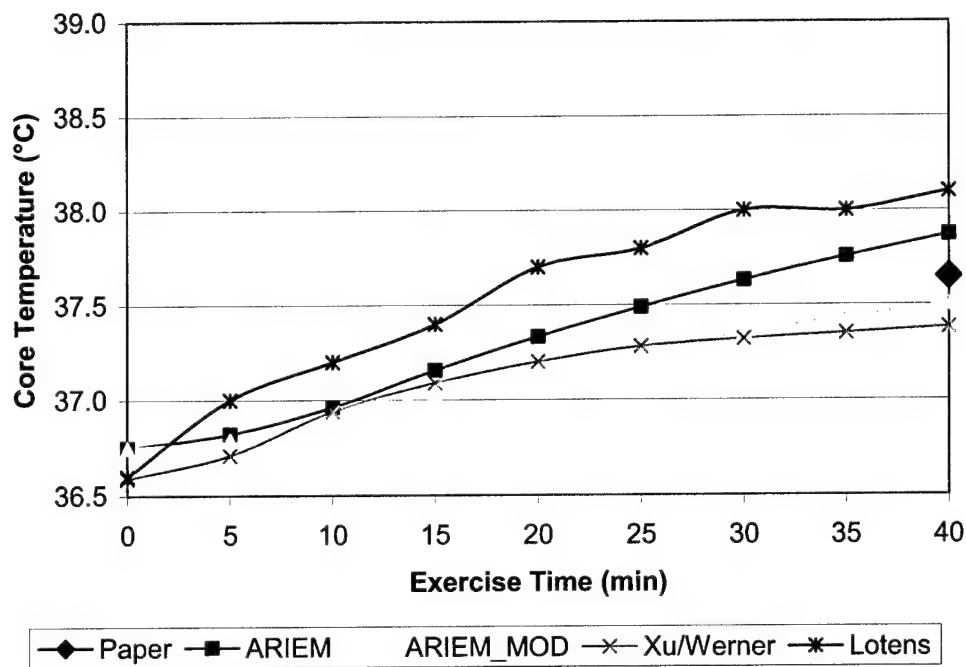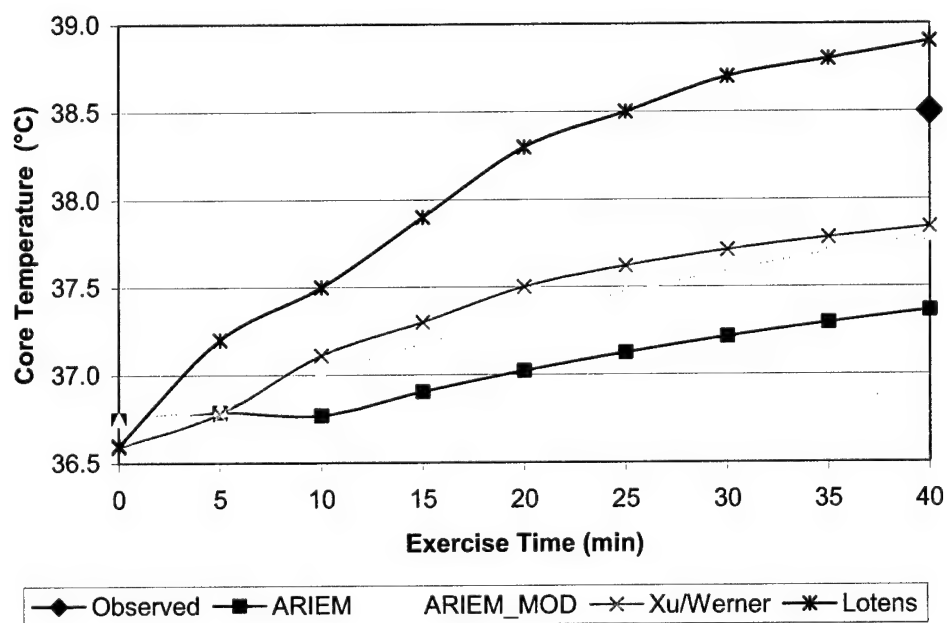**Figure 8.** *Comparison of predicted core temperatures from four models with measured Tc values*

reported by Montain et al [16] for exercise at 65% VO$_2$peak

3.6 Comparison 5: (Data from Amos and Egglestone [17])

Eight young male subjects who had been acclimatised by working in the heat to elevated core temperatures for five consecutive days exercised indoors on a motor-driven treadmill wearing the Disruptive Pattern Combat Uniform (DPCU) with webbing and two 1-litre water bottles for 100 minutes at 5 Km.h^{-1} and 6% slope (600 watt total metabolic rate). The average age of the subjects was 21 years, height 181 cm, weight 75.15 kg, VO$_2$peak 55.5 ml.min^{-1}.kg^{-1}. A body-fat content of 20% is assumed. Exercise was repeated in two environments: at 30°C, 60% RH and 40°C, 30% RH, both at a wind speed of 1.1 m.s^{-1}.

The Amos and Egglestone [17] data were used to adjust several coefficients to produce the ARIEM_MOD model. It would not be valid, therefore to attempt to gain information by comparing the performance of the ARIEM_MOD model with this set of experimental data, however the relevant curves are included for interest. The errors produced by the other models show how far the state of the art needs to progress before accurate predictions will be available for clothed subjects. Figures 9 and 10 show that the Lotens/Havenith model predicts an early overly rapid rate of rise in Tc and then Tc remains relatively constant, a trend which the experimental temperatures do not exhibit. The resultant prediction of final Tc actually compares very favourably with the ARIEM model which shows a curve shape similar to that of the experimental data albeit at a higher temperature and higher rate of rise. The Xu/Werner model predicts an early rate of rise which plateaus to a constant temperature that is lower than the measured Tc. This is reflected in the end-point errors and RMS errors shown in Table 1b and Table 2 respectively.

Figure 9. Comparison of predicted core temperatures from four models with measred Tc values reported by Amos and Egglestone [17] for exercise at 30°C and 60% RH
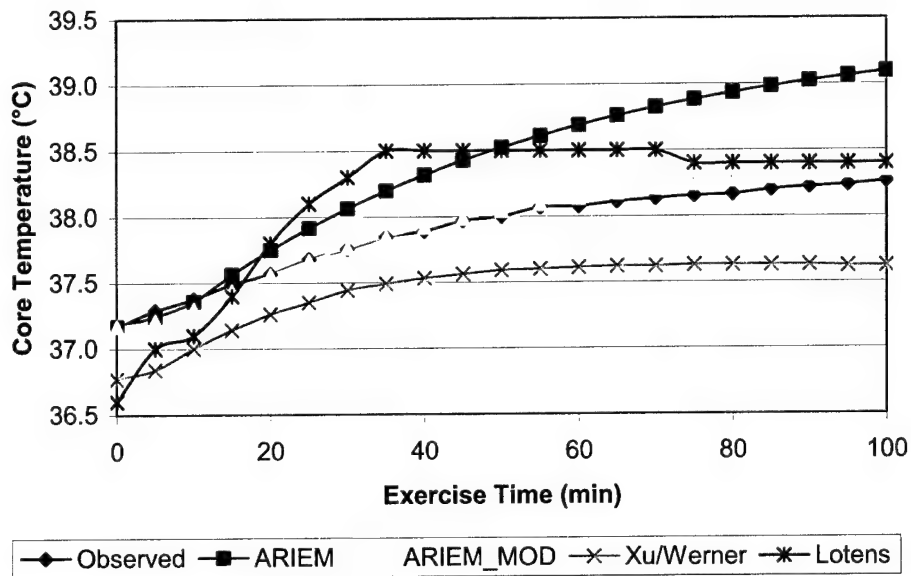

Figure 10. *Comparison of predicted core temperatures from four models with measured Tc values reported by Amos and Egglestone [17] for exercise at 40°C and 30% RH*
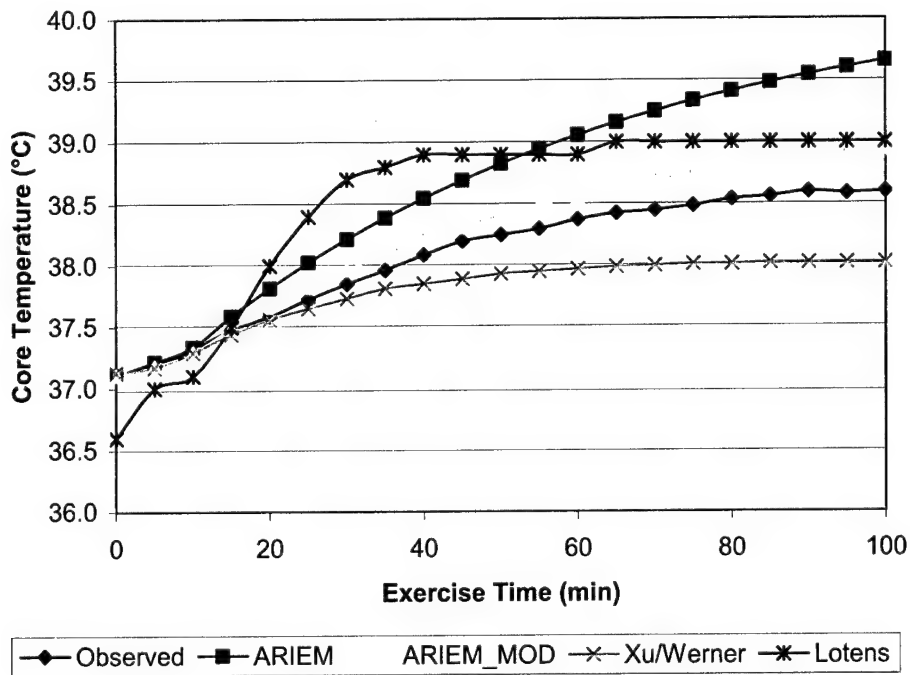
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4. Discussion

If one had to choose a model to be the best end-point predictor for the conditions in the Nadel et al [13] data then, as shown in Table 1a and Table 2, the ARIEM_MOD model performs best over the relatively short 30 minute period of the experimental protocol. From Figure 11 and Table 3, it is clear that should the exercise period be extended to 40, 50 or 60 minutes and the subjects body temperature continue the rising trend seen at the end of the experiment (and for work at 750 watt total metabolic rate this is a reasonable extrapolation), then all the models would generate larger errors with the ARIEM_MOD model still emerging as the best predictor of this new end-point Tc.

Table 3. Model errors against extrapolation of the data from Nadel et al [13] to 60 minutes

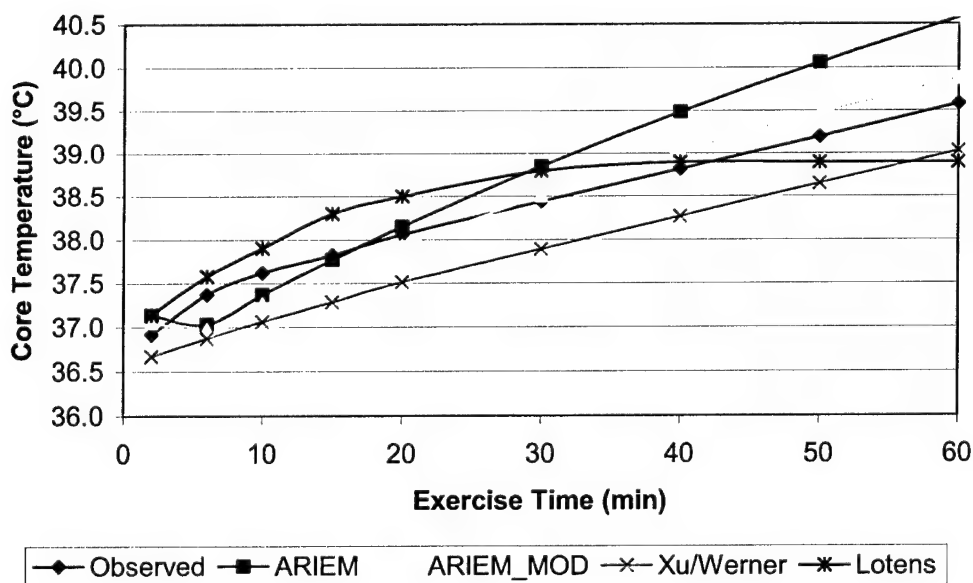| Model	ARIEM	ARIEM_MOD	Xu/Werner	Lotens/Havenith
Endpoint Error	1.00°C	0.30°C	-0.55°C	-0.68°C
RMS Error	0.54°C	0.25°C	0.50°C	0.35°C

Figure 11. Graph of extrapolations from the data of Nadel et al [13]

Only one of the papers from which data and model parameters were taken specified ambient wind speed and since all four models require this input, it was necessary for

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comparison with the other studies to assume the standard ambient wind speed of between 0.1 and 0.2 m.s^{-1} which is commonly attributable to air conditioning systems. Figure 12 displays the effect of varying wind speed on Tc as predicted by the ARIEM_MOD model. The data of Nadel et al [13] was chosen to demonstrate this effect because this study was based on exercise on a cycle ergometer and the activity of cycling generates less air motion than does walking on a treadmill. The effect of changes in ambient wind speed will therefore be greater than in the case of treadmill exercise.
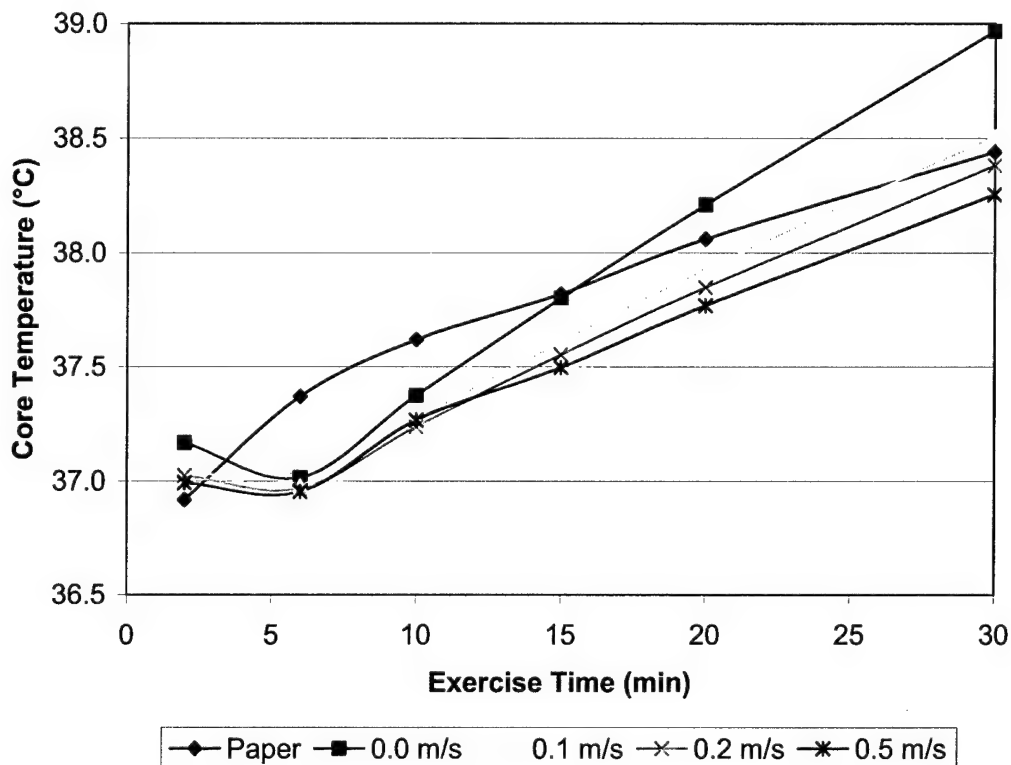
Figure 12. Comparison of predicted Tc from the ARIEM_MOD model at four wind speeds with measured Tc values from Nadel et al [13]

As is clearly shown in Figure 12, there is a substantial effect when wind speed is varied between zero and 0.5 m.s^{-1} and the best agreement with the selected experimental results occurs at a speed of 0.1 – 0.2 m.s^{-1}. This supports the author's assumption of no forced ventilation in this instance.

For most of the studies, it was necessary, in the absence of an accurate objective method, to estimate body fat content for use in the Lotens/Havenith and Xu/Werner models . Figure 13 indicates the impact of changes in body fat content at a constant total body weight using the Xu/Werner model on the Melin et al [15] experimental

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protocol and Tc data. It is clear from this chart that changing the fraction of body weight as fat from 5% to 30% results in only a 0.1°C decrease in the predicted end-point core temperature even though the exercise was at 50% VO$_2$peak (640 watt total metabolic rate) and is continued for a relatively long period. The same variations in body fat content introduced into the Lotens/Havenith model resulted in no change in core temperature predictions. Since the body fat content of experimental subjects will fall well within this range, it may be expected that little bias would be introduced by assuming body fat content of 20%.
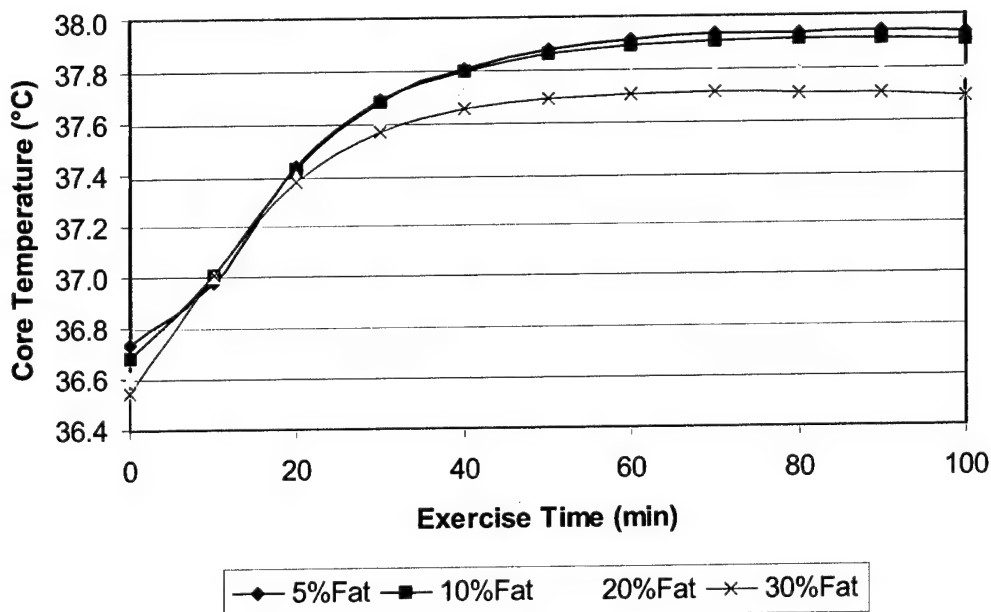
Figure 13. The effect of body fat content on Xu/Werner core temperature prediction

With the exception of the data from Amos and Egglestone [17], all of the above comparisons of model predictions against published data occur under conditions in which the experimental subjects wear minimal clothing. The ability of the models to predict contributions of clothing to heat stress are therefore essentially untested by those comparisons. When the models were tested against subjects wearing the Australian DPCU (a lightweight military uniform), prediction accuracy for all of the models was no better than the worst case for the lightly clothed experiments.

5. Conclusions

Based on the comparisons described in this paper, it is clear that all of the models may produce predictions of core temperature which have unacceptable errors under certain

conditions. The ARIEM_MOD model has consistently demonstrated superior accuracy of prediction compared with the other three models considered, showing a large error only under the highest work rate of Montain et al [16]. The ARIEM model performs acceptably most often at work rates less than 350 watt but also did reasonably well at the 680 watt reported by Montain et al [16]. The Lotens/Havenith model consistently showed high initial rates of temperature rise and where the exercise protocol was sufficiently extended, a plateau of constant temperature not exhibited by the experimental data but which often achieves a final temperature close to that obtained by measurement. These observations suggest that the heat storage algorithms of the Lotens/Havenith model require further revision. The Xu/Werner model also displayed an initial temperature rise followed by a plateau. The initial rate of temperature rise matched that of the experimental data while the plateau temperature was generally too low. This model bases its predictions on extensive data files of coefficients and physical constants for which the origins are unknown to this author but are presumably drawn from experimental data. Its predictions may therefore be improved by selecting more appropriate data values for these files.

6. Recommendations

The ARIEM_MOD model has consistently demonstrated superior accuracy of prediction compared with the other three models considered. It is therefore recommended that his model in its current form is the first choice for modelling human responses to thermal stress. While there is room for improvement, further development of this model would require laboratory trials on a massive scale and it is doubtful if the necessary resources can be made available to support such a study. Although the Lotens/Havenith and Xu/Werner models show discrepancies in Tc prediction they are both amenable to incremental development and validation by manipulation of individual algorithms or physical or physiological parameters. It is recommended therefore that development of the Xu/Werner and Lotens/Havenith models be pursued.

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19. ABSTRACT

The core temperature predictions from four computer models of the human thermoregulatory response were compared with results from laboratory exercise studies published locally and in the open literature. Although none of the models were able to predict deep body temperatures to within an accuracy of 0.1°C to 0.5°C in all instances, the model from the United States Army Research Institute of Environmental Medicine (ARIEM) in the form modified by DSTO performed better than the original and better than the rational models published by Xu and Werner and by Lotens and Havenith. However these latter two models are amenable to incremental improvements resulting from relatively small studies and it is therefore recommended that their development be continued at DSTO.